Predicting The Neutrino Flux at T2K

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for the T2K collaboration
Outline

- Introduction
- T2K neutrino beam MC
- Flux predictions
- Systematic errors
- Conclusions
T2K experiment at a glance

\[ \text{Prob}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 [1.27\Delta m^2_{23} L(\text{km})/E(\text{GeV})] \]

\[ \text{Prob}(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 [1.27\Delta m^2_{23} L(\text{km})/E(\text{GeV})] \]

- 30 GeV proton beam from J-PARC MR
- Muon monitors measure muons from pion decay
- On-axis detector (INGRID) measures neutrino rate and neutrino beam direction
- Off-axis detector (ND280) measures spectra for various neutrino interactions
- SK detector measures oscillated flux
Off-axis $\nu$ beam

- Narrow band beam
  - Pions with different momenta contribute to a neutrino with same energy
- For OA 2.5° peaks is $\sim$0.6 GeV – oscillation maximum for $L = 295$ km baseline

- Precision measurement of oscillation parameters
  - High statistics in the region of the oscillation signal
  - Less background caused by high energy neutrinos
- Need a stable $\nu$ beam
  - Beam direction change = shift in energy peak @ an off-axis detector
Input from the proton beam-line

- Stability of the off-axis neutrino beam requires a stable proton beam
- Proton monitors measure position, angle, and beam profile at the target
  - Position uncertainty < 1mm, angle uncertainty < 0.5 mrad (equivalent ~ 0.5 mm)
  - 1mm ~ 1mrad change in ν beam direction
- From profile measurements can evaluate targeting efficiency 99.4%
- Input to beam MC
Confirming the off-axis angle

On-axis (INGRID) detector measurement of υ direction

Beam direction is confirmed to be stable < 1mrad by muon monitor and INGRID measurements

1 mrad ~ 2% shift of the energy peak @ SK
Why flux predictions are important

1. Extrapolating measurements at the ND to make predictions at the FD to measure neutrino oscillation parameters (1 bin analysis):

\[ N_{ND}^{obs} \times \text{Prob}_{\nu_\mu \to \nu_\tau}(\theta, \Delta m^2) \times \left( \frac{N_{FD}^{MC}}{N_{ND}^{MC}} \right) = N_{FD}^{exp}(\theta, \Delta m^2) \]

- Observed # of events at ND
- Extrapolation factor derived from beam MC
- Expected # of events at FD

2. Flux prediction at the ND for cross-section measurements

Goal of the T2K beam Monte Carlo is to make the flux predictions and evaluate associated uncertainties based on external experimental data as much as possible.
T2K beam Monte Carlo

FLUKA 2008.3d simulation
- p interactions inside carbon target

30 GeV p with measured parameters

π⁺

π⁺

Target
T2K beam Monte Carlo

FLUKA 2008.3d simulation
- $p$ interactions inside carbon target

GEANT3 (w/ GCALOR)
- Tracking through horn fields & decay volume
- Neutrino producing decays

30 GeV $p$
with measured parameters

Target

Horn

$\pi^+$

$\pi^+$

$\pi^+$

$\pi^+$

$\pi^+$
T2K beam Monte Carlo

FLUKA 2008.3d simulation
- $p$ interactions inside carbon target

GEANT3 (w/ GCALOR)
- Tracking through horn fields & decay volume
- Neutrino producing decays

Adjust flux predictions using available external data

Neutrino Fluxes at Near and Far detectors based on experimental data

30 GeV $p$ with measured parameters

Target

Horn

$\pi^+$
Pions contribute to most of $\nu_{\mu}$ in the oscillation region and to low energy $\nu_{e}$ intrinsic background at the osc. peak:

$\pi^+ \rightarrow \mu^+ \nu_{\mu}$

$\mu^+ \rightarrow e^+ \bar{\nu}_{\mu} \nu_{e}$

NA61 pion data would help with both
NA61 pion data

NA61 experiment measures particle production from C at T2K beam energy (30 GeV)

Phase-space of pion contributing to the SK $\nu_\mu$ flux with NA61 coverage

Covers almost all of the relevant pion phase-space for $\nu_\mu$ production at T2K

Gives a good handle on low energy $\nu_e$ production as well

N. Abgrall et. al., arXiv:1102.0983 [hep-ex]
Accepted by Phys. Rev. C (2011)
NA61 pion data sets

- Data taken with a thin target (~0.04 \( \lambda_I \)) <= Results from 2007 run are available
- Data taken with a replica of the T2K target (long target~2 \( \lambda_I \)) <= Analysis is in progress
- How to make use of the currently available NA61 data?
Store information about the interactions leading to a produced $\nu$: Interaction point, outgoing particle type, its momentum, and material where the interaction occurred.

- Weight the distribution of pions from proton interactions according to the NA61 data.
- Correct the interaction rates of particles in a given material.
- Study production of other ($K, p, n,...$) particles to compare with existing data and assign appropriate errors.
## Secondary particle contributions to SK flux

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\nu_\mu$ Fraction</th>
<th>$\nu_e$ Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>69.5%</td>
<td>40.5%</td>
</tr>
<tr>
<td>$K^{+/0}$</td>
<td>7.7%</td>
<td>39.2%</td>
</tr>
<tr>
<td>$\pi^{+/0}$</td>
<td>15.8%</td>
<td>13.6%</td>
</tr>
<tr>
<td>$\pi^{+/0}$</td>
<td>5.2%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Other ($\Lambda$, $\Sigma$, ...)</td>
<td>1.8%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Weighting events

Tune (weight) T2K pion production to the NA61 data

\[ w_{\pi}(p, \theta) = \frac{\frac{dn_{\text{NA61}}^2}{dpd\Omega}}{\frac{dn_{\text{MC}}^2}{dpd\Omega}} \]

Weight = Measured / Modeled pion production multiplicity

\[ \frac{dn}{dpd\Omega} = \frac{1}{\sigma_{\text{prod}}} \frac{d\sigma_{\pi}}{dpd\Omega} \]
Weighting events

Interactions with the material around the target (mostly Al of the horns)

Long target => absorption of produced pions

Need to account for differences in inelastic cross-section (differences in the interaction rates) between data and MC
Tuning flux predictions
Tuning secondary pion production with NA61 data

FLUKA is mostly in agreement with NA61 data.

A weight of 1 is assigned outside NA61 covered phase-space.
Tertiary pions contribute ~12% to flux. Can use NA61 data to tune these. Use $x_F$ scaling to scale to different beam momenta.

30 GeV beam $p$

Secondary $p$

$\pi(x_F - p_T)$

$\pi^+/\pi^-$

Tertiary pions contribute ~12% to flux. Can use NA61 data to tune these. Use $x_F$ scaling to scale to different beam momenta.

$\pi(x_F - p_T)$

$x_F = \frac{p_L^{CM}}{p_{CM}^{Max}}$
Tuning flux predictions

Tuning interaction rate

Interaction probability depends on mean interaction length

\[ \lambda = \frac{A}{N_A \rho \sigma_{\text{prod}}} \]

\[ \sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}} \]

- Compare models to production cross-section data for interacting \( p, \pi^\pm, \) and \( K^\pm \) on C and Al (graphite target and aluminum horns)

- GCALOR has sizable discrepancy with the data => tune interaction rate outside of the target

- Need to adjust:
  1. Weight for the survival probability
  2. Weight for the interaction probability

\[ w_{\text{out}} = e^{-x/(\lambda_{\text{data}}-\lambda_{\text{MC}})} \]

\[ w_{\text{int}} = \frac{\lambda_{\text{MC}}}{\lambda_{\text{data}}} e^{-x/(\lambda_{\text{data}}-\lambda_{\text{MC}})} \]
Neutrino parents

“Secondary Hadrons”: hadrons from beam protons

“Tertiary Hadrons – In Target”: hadrons from re-interactions inside the target

“Tertiary Hadrons – Out of Target”: hadrons from re-interaction outside of the target
Flux prediction tuning: final results

- Adjustments to FLUKA+GEANT3 beam MC based on data
  - Pion production: ~10 (5) % flux increase for $\nu_\mu$ ($\nu_e$)
  - Interaction rate outside of the target: a few percent correction
### Particle production systematics

<table>
<thead>
<tr>
<th>Particle</th>
<th>Fraction of $\nu_\mu$</th>
<th>Fraction of $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>69.5%</td>
<td>40.5%</td>
</tr>
<tr>
<td>$p$</td>
<td>7.7%</td>
<td>39.2%</td>
</tr>
<tr>
<td>$p$</td>
<td>15.8%</td>
<td>13.6%</td>
</tr>
<tr>
<td>$p$</td>
<td>5.2%</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

- **Systematic error of NA61 pion production measurement**
- **Discrepancy between existing data* & FLUKA**
  \[ K_L^0 = \frac{1}{4} (K^+ + 3K^-) \]
- **Discrepancy between existing data* & FLUKA**
- **NA61 pion error applied based on isospin invariance**
- No errors are assigned on other ($\Lambda, \Sigma, ...$) particles: ~2% contribution to the flux

*Eichten et. al. (*Nucl. Phys. B* 44 333(1972))
### Other systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Evaluated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction rate of particles inside material</td>
<td>Uncertainty in the size of QE component in data ($\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$)</td>
</tr>
<tr>
<td>$\nu$ beam direction (off-axis angle)</td>
<td>INGRID measurement</td>
</tr>
<tr>
<td>Proton beam parameters</td>
<td>Uncertainties in p monitor measurements</td>
</tr>
<tr>
<td>Horn absolute currents</td>
<td>Uncertainties in current measurements</td>
</tr>
<tr>
<td>Target &amp; horn alignments</td>
<td>Survey results</td>
</tr>
</tbody>
</table>
SK $\nu_\mu$ and $\nu_e$ error envelopes

The overall uncertainty is on the order of ~15% in the oscillation region (<1 GeV)

Kaon uncertainties become dominant for $\nu_e$ energies >1 GeV
Flux uncertainties on number of $\nu_e$ events ($\theta_{13} = 0$)

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$R_{ND280}^{\mu,MC}$</th>
<th>$N_{SK}^{e,MC}$</th>
<th>$N_{SK}^{e,MC} / R_{ND280}^{\mu,MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion production</td>
<td>5.7%</td>
<td>6.2%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Kaon production</td>
<td>10.0%</td>
<td>11.1%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Nucleon production</td>
<td>5.9%</td>
<td>6.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Production cross-section</td>
<td>7.7%</td>
<td>6.9%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Off-axis angle</td>
<td>2.7%</td>
<td>2.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Proton beam</td>
<td>2.2%</td>
<td>0.0%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Horn current</td>
<td>0.5%</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Alignment</td>
<td>0.7%</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total</td>
<td>15.4%</td>
<td>16.1%</td>
<td>8.5%</td>
</tr>
</tbody>
</table>

With (without) F/N cancellation the flux uncertainty on the number of expected $\nu_e$ events is 8.5% (16.1%).

$$N_{SK}^{exp} = R_{ND280}^{\mu,Data} \times \left( N_{SK}^{e,MC} / R_{ND280}^{\mu,MC} \right)$$

cf. total uncertainty 23% (Phys. Rev. Lett. 107, 041801 (2011))
Shape error for SK $\nu_\mu$ flux

- Uncertainty on the flux shape for $\nu_\mu$ disappearance measurement
- Necessary to consider correlations between different neutrino energy bins

- Construct flux covariance matrix for each error source
  - Requires a prescription for correlations of the NA61 pion production uncertainties
Current agreement with the near detector measurements

ND280 $\nu_\mu$ CC event rate, $R_{\mu,Data(MC)}^{ND}$, ratio (Data/MC*)

$$R_{ND}^{\mu,Data} / R_{ND}^{\mu,MC} = 1.036 \pm 0.028\text{(stat.)}^{+0.044}_{-0.037}\text{(det.syst.)} \pm 0.038\text{(phys.syst.)}$$

INGRID event rate, $R_{Data(MC)}$, ratio (Data/MC*)

$$R_{Data} / R_{MC} = 1.057 \pm 0.001\text{(stat.)} \pm 0.040\text{(syst.)}$$

Good agreement between Data and MC

*Flux systematic uncertainties are not included in the error
Conclusions

● T2K flux is estimated based on data
  • Correction factors to pion production in FLUKA2008 are obtained using NA61 2007 thin target data
    – $\nu_\mu$ flux is increased by ~10% and $\nu_e$ by ~5%
  • Correction to the interaction rate based on production cross-section data increases flux at the peak by ~2%
● Good agreement with the near detector measurements
● The evaluation of the flux uncertainties is mostly based on measurements and external available data
● Flux uncertainty on the expected number of $\nu_e$ events is 8.5%
Outlook

- Significant reduction of $K^+$ production uncertainty with NA61 $K^+$ measurement
- Substantial improvement of the absolute flux uncertainties with the NA61 hadron production measurement with the T2K replica target
Back-up slides
Proton beam position at the target

- Beam center and angle @ the target is extracted from the monitor measurements

X

ESM19

SSEM18

baffle
target

SSEM19

OTR

Y

SSEM18

baffle
target

SSEM19

OTR

Beam was lowered
Proton beam profile at the target

Optics fit to the profile monitor measurements to extract beam width @ target

Fraction of protons on 26° target surface using extrapolated beam center and width at the target (effect of beam angle and divergence are ignored)
Neutrino fluxes @ off-axis detectors

**ND280 fluxes**

**SK fluxes (no. osc)**

![Graph showing ND280 fluxes](image1)

![Graph showing SK fluxes](image2)
Eichten et., al. measured particle ($\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$) production from thin Be, $B_4C$, Al, Cu, and Pb targets with 24 GeV/c proton beam.

- Use Be data for $K^\pm$ and $p$ to estimate uncertainties on kaon and nucleon production.
- Use $x_F$ to account for different beam energy.
- Error is assigned based on difference between data and FLUKA predictions for 24 GeV/c $p$ on Be to data.
  - Includes:
    - experimental error
    - 10% error due to material scaling (Be -> C)
Flux prediction tunes for ND280: all nu flavours

![Graphs showing reweighting factors for different neutrino flavors.](image)
Flux prediction tunes for SK: all nu flavours

![Graphs showing reweighting factors for different neutrino flavours](image)
Hadron parent production: ND280

ND280 $\nu_\mu$: Parent Hadron Production

ND280 $\nu_e$: Parent Hadron Production
Hadron parent production: SK

SK $\nu_\mu$: Parent Hadron Production

$E_\nu$ (GeV)

Flux (cm$^{-2}$ $\cdot$ 10$^{21}$ POT $\cdot$ 100 MeV)

- Secondary Hadron
- Tertiary Hadron - In Target
- Tertiary Hadron - Out of Target

SK $\bar{\nu}_\mu$: Parent Hadron Production

$E_\nu$ (GeV)

Flux (cm$^{-2}$ $\cdot$ 10$^{21}$ POT $\cdot$ 100 MeV)

- Secondary Hadron
- Tertiary Hadron - In Target
- Tertiary Hadron - Out of Target

SK $\nu_e$: Parent Hadron Production

$E_\nu$ (GeV)

Flux (cm$^{-2}$ $\cdot$ 10$^{21}$ POT $\cdot$ 100 MeV)

- Secondary Hadron
- Tertiary Hadron - In Target
- Tertiary Hadron - Out of Target

SK $\bar{\nu}_e$: Parent Hadron Production

$E_\nu$ (GeV)

Flux (cm$^{-2}$ $\cdot$ 10$^{21}$ POT $\cdot$ 100 MeV)

- Secondary Hadron
- Tertiary Hadron - In Target
- Tertiary Hadron - Out of Target
Particle contributions

Proportions of particles produced by the beam protons

Secondary protons re-interact to produce secondaries which contribute to the neutrino flux

<table>
<thead>
<tr>
<th>Secondary particle</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>67.5%</td>
<td>11.7%</td>
<td>38.8%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>2.0%</td>
<td>36.6%</td>
<td>1.7%</td>
<td>4.0%</td>
</tr>
<tr>
<td>$K^+$</td>
<td>4.8%</td>
<td>2.2%</td>
<td>26.9%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$K^-$</td>
<td>0.1%</td>
<td>4.9%</td>
<td>0.4%</td>
<td>13.0%</td>
</tr>
<tr>
<td>$K^0_L$</td>
<td>2.8%</td>
<td>4.4%</td>
<td>11.9%</td>
<td>55.8%</td>
</tr>
<tr>
<td>Proton</td>
<td>15.8%</td>
<td>21.4%</td>
<td>13.6%</td>
<td>13.0%</td>
</tr>
<tr>
<td>Neutron</td>
<td>5.2%</td>
<td>13.6%</td>
<td>5.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Others (Λ, Σ, η, etc.)</td>
<td>1.8%</td>
<td>5.2%</td>
<td>1.5%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tertiary particle</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>12.3%</td>
<td>2.1%</td>
<td>6.6%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>0.2%</td>
<td>11.5%</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$K^+$</td>
<td>0.6%</td>
<td>0.3%</td>
<td>3.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$K^-$</td>
<td>0.0%</td>
<td>0.7%</td>
<td>0.0%</td>
<td>1.6%</td>
</tr>
<tr>
<td>$K^0_L$</td>
<td>0.3%</td>
<td>0.5%</td>
<td>1.4%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Proton</td>
<td>1.7%</td>
<td>3.3%</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Neutron</td>
<td>0.5%</td>
<td>2.1%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Others (Λ, Σ, η, etc.)</td>
<td>0.2%</td>
<td>0.9%</td>
<td>0.2%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Total (secondary proton)</td>
<td>15.8%</td>
<td>21.4%</td>
<td>13.6%</td>
<td>13.0%</td>
</tr>
</tbody>
</table>
Error envelopes

Error on the flux in the oscillation region ~15%

High energy tail is dominated by kaon uncertainty 20-50%